# The Case for Physically-based Distributed Hydrologic Modeling Approaches for the US Army Corps of Engineers Civil Works Projects

[1]Charles W. Downer, [1]Jeff Jorgeson, [2]Fred L. Ogden, [3]Pierre Julien, [4]William D. Martin, [5]Earl Edris,[6]Russell S. Harmon, [7]Ehab Meselhe, and [8]Jim Nelson

## Abstract

Over the course of the past decade, the US Army Engineer Research and Development Center (ERDC) and Army Research Office (ARO) have supported the development of the physically-based, hydrologic modeling approach for the calculation of stream flows and depths, soil moistures, and sediment erosion, transport, and deposition in support of the US armed forces in both military operations and environmental management of military lands. These efforts have resulted in the development of the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. The GSSHA model is a multi-dimensional, physically-based, hydrologic model intended to be used for detailed hydrologic analysis and in the design of environmental management and restoration projects. The GSSHA model, and its predecessor CASC2D, have been verified for the prediction of flow in both arid and humid regions, and soil moistures and sediment discharge in humid regions. The fully distributed nature of the model easily accommodates incorporation of spatial heterogeneity. The physical nature of the model enhances the confidence in using the model for design purposes. The GSSHA model is fully coupled to the Department of Defense (DoD) Watershed Modeling System (WMS) and compliments a suite of hydrologic modeling tools available in WMS including HEC-1, TR-20, and HSPF. Current and future development efforts at ERDC, the University of Connecticut, Colorado State University, Brigham Young University and the University of Louisiana at Lafayette include the development of improved channel dynamics and sub-surface pipe flow networks, sediment transport algorithms, and contaminant transport. While the model has been used at a number of both military and civil sites, its ability to be used for analysis of civil works projects has been underutilized. In this paper, the applicability and potential advantages of using the physically-based GSSHA hydrologic model for US Army Corps of Engineers civil works projects will be discussed.

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[1] Research Hydraulic Engineer, Coastal and Hydraulic Laboratory, US Army Engineer Research and Development Center (ERDC), Vicksburg, MS. (601) 634-2473, dowenrc@wes.army.mil.
[2] Associate Professor, Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT.
[3] Professor, Department of Civil Engineering, Colorado State University, Fort Collins, CO.
[4] Deputy Director, Coastal and Hydraulics Laboratory, US Army ERDC, Vicksburg, MS.
[5] Chief, Hydrologic Systems Branch, US Army ERDC, Vicksburg, MS.
[6] Mechanical and Environmental Science Division, Army Research Office, Research Triangle Park, NC.
[7] Associate Professor, Civil Engineering Department, University of Louisiana at Lafayette, Lafayette, LA.
[8] Assistant Professor, Department of Civil and Environmental Engineering, Brigham Young University, Provo, UT.

## Introduction

The processes that control infiltration, runoff production, stream flow, sediment erosion and transport are complex and, therefore, difficult to quantify and are highly uncertain. Thus, the traditional approach to hydrologic watershed modeling has been to oversimplify the description of the processes. Most hydrologic models are empirically based and attempt to merely reproduce observed flow without adequately describing the processes responsible for observed results. However, traditional methods are being challenged. High-speed computers and improved data sources and analysis techniques are making it possible to better describe and numerically simulate the actual processes that produce runoff. Models that attempt to describe the processes involved in runoff production and routing are termed "physically-based models". Models that attempt to account for the spatial variability within the watershed are termed "distributed models". These models have been used primarily as research tools; their proper application is an area of active investigation. The development and linkage of hydrologic models with geographic information systems (GIS), and the increasing availability of digital data, have made the application of physically based, distributed models more feasible.

The simplest way to model a watershed is to treat the watershed as single unit with uniform properties throughout. A slightly more complex approach is to divide the watershed into sub-watersheds, with each sub-watershed having uniform characteristics. Such models are commonly referred to as "lumped-parameter models" because the properties of the watershed or sub-watersheds are lumped together. Because of the spatial coarseness of the model, the process descriptions within the watershed or sub-watershed are conceptual or empirical in nature (Nikolaidis et al., 1996; Ponce and Hawkins, 1996). The advantages of lumped models are that they are conceptually simple, easy to implement, and have seen wide application (Beven, 1989; Ponce and Hawkins, 1996).

The concept behind lumped parameter models is that when a complex suite of processes are integrated over sufficient time and space, the highly non-linear system will produce linear results. This basic idea proves adequate, provided the space and time intervals are sufficient. Some limitations of this approach are described below. Physically-based models work on the premise that at small enough scales (grid scale) the basic physics can be explicitly described and integrated to produce the watershed response. This approach has been verified at both the watershed and grid scale for several measurement statistics. The drawback to this approach is the computational burden and the need to assign parameters to every grid cell for each process included in the model.

Physically-based, distributed models employ spatially distributed properties within a watershed with a process-based approach. Potential advantages of this approach are that it can be used to model watershed changes (Nikolaidis et al., 1996), or analyze different management strategies (Wang and Hjelmfelt, 1998). Because the models are physically based they may be useful for extrapolating the models outside the calibration range (Beven, 1985). They also are useful for understanding hydrologic processes (Woolhiser, 1996). Distributed models also have the potential to model inherently distributed processes, such as water quality (Abbott et al., 1986).

**Limitations of Empirically-Based, Lumped Parameter Models**

While useful, traditional empirically-based lumped parameter models have significant, and well-documented, limitations, including:

1. Simplified descriptions of physical processes,
2. Lack of verifiable results,
3. Inability to use the models outside the range of calibration, and
4. Lack of spatial heterogeneity in the models.

**Simplified Descriptions of Physical Processes.** Traditional hydrologic models include rudimentary descriptions of physical processes to simulate complex reactions of watersheds to hydro-meteorological inputs. Runoff is typically computed by reducing rainfall volume or intensity by a factor based on a composite of features in a sub-basin, i.e. SCS method. This runoff is routed to the watershed outlet with a series of channel "links" describing flow with a power function relating discharge to stage. Such models may include empirical representations of groundwater, yet Arnold et al. (1993) found that attempts to link surface water and groundwater models were insufficient because recharge was calculated using empirical methods.
The HSPF (Bicknell, et al., 1997) model provides an example of the lumped-parameter conceptual modeling approach. According to Bergman and Donnangelo (2000):

> Conceptually, HSPF simulates the hydrology of a watershed by a network of linear and nonlinear storages that represent the components of the natural system. Inflow and outflow of these storages are controlled by parameters that describe the physical characteristics of each component.

Descriptions of sediment erosion and transport and water quality constituents are equally simplified. In HSPF sediments on the overland flow plane are eroded with an empirical equation based on a single value of rainfall intensity in the sub-basin and transported based upon total flow from the sub-basin. There is no accounting for water depth, velocity, particle size and density in the empirical relationships, because none of these values are known. It is highly questionable that the effects of Best Management Practices (BMPs) for controlling sediments can be analyzed with such crude descriptions of processes that control the effectives of the BMPs.

**Lack of Verifiable Results.** Given the crude approximation of processes in traditional hydrologic models, representation of discharge patterns from watersheds depends on extensive calibration requiring a great deal of data. Years of observed data (5 years is a recommended value (Refsgaard and Knudsen, 1996)) may be necessary to incorporate the desired range of flows into the calibration process.

Contrary to prevailing opinion in the hydrologic modeling community, the scientific literature demonstrates these traditional models are not providing accurate predictions of discharge. Loague and Freeze (1985) conducted testing of three simple modeling approaches, regression analysis, unit hydrograph approach, and an quasi-physically based event model, and found that all the models "...show surprisingly poor efficiencies for all models for all catchments." When alluding to the fact that the models produced poor results and did not represent the physical system they interject "We suspect that this is the case with most, if not all conceptual models currently in use." Michaud and Sorooshian (1994) compared two physically-based models with a lumped parameter model based on the SCS method, and found that the physically based models greatly outperformed the SCS based model but still lacked sufficient accuracy. The inability of the lumped-parameter model to include the spatial heterogeneity of rainfall and runoff was cited as a major cause of poor performance. Naef (1981) tested six conceptual rainfall-runoff models, from the very simple to the most complex, and found none of them able to reproduce the rainfall-runoff process. Chiew et al. (1993) in a comparison of six rainfall-runoff models found that only the most complex model was capable of reproducing daily flows. The simple models were useful for computing monthly and annual flows. This makes sense given the bases for simple empirical modeling in the first place.

Researchers have found that simple models are particularly poor at predicting discharge in arid regions. When comparing a conceptual modeling approach to a more complex model, Gan and Burgess (1990 a, b) demonstrated that the conceptual modeling approach "...could not predict reliably the response to extreme rainfall that was predicted by the complex model." These are the very events that will be of the most interest in sediment erosion and delivery. Military interest in the development of physics-based, distributed modeling arose from the need to have better predictions of discharge in arid regions. According to Ogden and Helig (2001), errors in hydrologic predictions will be amplified in sediment runoff predictions.

**Extending the models beyond the range of calibration.** Many researchers have discussed the limitation of using conceptual models outside the range of calibration due to the empirical nature of the equations employed (e.g. Naef, 1981; Beven, 1985; and Nikolaidis et al. 1996). The calibration process tunes the empirical equations to the systems being studied, under the calibration conditions. Because the physics are greatly simplified, the parameters must implicitly account for physics not explicitly described. As such, the parameter values are dependent on the calibration conditions. If the system changes, the calibrated model parameters will likely not adequately describe the new system because the physics implicitly included in the parameter set no longer exist. The difficulty in assigning meaningful rainfall partitioning coefficients is discussed by Hughes and Beater (1989) and Ponce and Hawkins (1996).

**Lack of spatial heterogeneity.** While Naef (1981) and others have shown that the empirical modeling approach fails to produce satisfactory results in reproducing discharge, the lack of spatial heterogeneity in the lumped-parameter approach can be of even greater import in modeling sediments and water quality constituents. Past modeling efforts demonstrate the need for spatial heterogeneity. In attempting to simulate overland sediment erosion in the Goodwin Creek Experimental Watershed (GCEW) with the physically-based, distributed model GSSHA (Downer and Ogden, 2003a), Daraio (2002) found that sediment concentrations in one stream reach in sub-watersheds produced much higher sediment loads to the stream, on a per area basins, than any other stream reach. Slopes, land use, and soil types were similar in all the basins. While agriculture fields represented only a small percentage (13%) of the area in any of these basins this particular reach had a small cultivated field located immediately next to the stream reach. There was no chance for sediment from the field to deposit in pastures or forested areas. The bulk of the sediment load to this stream reach was determined to originate from this field. Although the field appeared to be insignificant due to its overall contributed area to the stream reach, the field, in fact, turned out to be critical because of its location. This type of information is completely lost when the watershed is discretized into smaller sub-watersheds, which are not able to correlate the location of a cultivated field to a stream. Field data and modeling efforts of Ogden and Helig (2001) show that "Peak sediment flux and sediment runoff volume data from Goodwin Creek reveal that spatial variability of rainfall and watershed characteristics plays an important role in erosion dynamics at the sub-watershed scale."

Utilization of modeling tools such as the Watershed Modeling System (WMS) (Nelson, 2001) or BASINS which capitalize on readily available GIS data (e.g., DEMs, soils, land use, roads, etc.) to support model development and application makes it easy to lose site of the fact that (1) the final conceptual model input may very well be a composite of these distributed factors, and (2) that the descriptions of the watershed responses are highly empirical. For example, for the most part, relatively simple process descriptions are included in HSPF. The coefficients used in the HSPF model must implicitly account for a number of processes not explicitly simulated. This makes parameterization of the model critical to success and makes determination of parameter values without calibration a highly risky proposition (Carrubba, 2000). As discussed by Munson (1998), HSPF parameterization for a typical model deployment is a difficult task alone:

> It quickly became apparent that little data exists to distinguish the hydrologic characteristics among land uses. Indeed, this has always been problematic in HSPF [18]. When setting parameters such as lower zone storage, for example, there is no empirical data to support different LZSN values for different land uses. It makes intuitive sense that wetlands should be able to store more water than forest, which stores more than residential land. However, the magnitudes of these differences can only be guessed at. If the average calibrated value of LZSN is about 15 inches, then any combination of LZSN values should give the same results if they average to fifteen.

**Summary.** It is clear from the literature that no existing model has solved the rainfall-runoff or overland sediment transport problem, and that research in these areas is needed. Indeed, a common criticism of all hydrologic models is that they do not include the critical physical processes that control stream flow. This incomplete physical description often requires that the model be subjected to an extensive, sometimes indefensible, calibration process to reproduce observed results (Beven, 1985). Clearly, there is a need for applicable models that include the dominant processes required in watershed analysis.

**The Gridded Surface Subsurface Hydrologic Analysis (GSSHA) Model**

The GSSHA model development has been, and continues to be, focused on addressing known inadequacies of currently available models. The principal objective of the GSSHA effort is to develop a practical numerical tool that correctly identifies and realistically models important watersheds processes. The model simulates different types of runoff production and determines the controlling physical processes in watersheds, i.e. infiltration excess, saturated source areas, and groundwater discharge. This eliminates, or greatly reduces, the subjectivity in model selection because it removes the need to identify the controlling processes prior to model selection. According to Klemes (1986), a good mathematical model must work well for the right reasons and must reflect the essential features of the physical prototype. Therefore, the equations of continuity and momentum that describe flow and transport are solved with mass conserving methods.

Despite the attention to mathematical rigor the model is applicable to practical problems. Currently the model is being applied to watersheds from field size up to areas of 1500 $mi^2$, and simulation times are sufficiently short to be used for real-time forecasting. When the parallel version of the model is complete, the model will be applicable to even larger, regional problems. The model is applicable, and verified, in both arid and humid regions. The model also makes use of available sources of distributed data and is linked to the powerful graphical user interface WMS that facilitates data preparation and results analysis.

The GSSHA model and/or the methods taken from *CASC2D* (Ogden and Julien, 2002) and employed in *GSSHA*, can be used to simulate the following types of hydrologic variables:

- Stream discharge in Hortonian basins (Doe et al., 1996; Ogden et al., 2000; Senarath et. al., 2000; Downer et al., 2002; Downer and Ogden, 2003b)
- Stream discharge in non-Hortonian and mixed runoff basins. (Downer, 2002)
- Soil moistures in Hortonian basins. (Downer and Ogden, 2003b).
- Sediment discharge in Hortonian basins (Johnson, 1997; Ogden and Helig, 2001; Daraio, 2002; Sanchez, 2002).

The levels of accuracy obtained with GSSHA in predicting short time scale stream flow, individual events, and hourly flows are unsurpassed in the literature (Senarath et al, 2000; Downer, 2002; and Downer and Ogden 2003b). In a direct comparison of the ability to predict outlet discharge in a small urbanizing water, Niedzialek and Ogden (2003) found GSSHA outperformed the USACE lumped-parameter model HEC-1 (USACE, 1985). Properly simulating individual events is critical in analyzing sediment transport and in efforts to control sediment within a watershed. The ability to simulate groundwater/surface water interaction along with the ability to precisely locate groundwater seeps to the stream network allowed the successful modeling of contaminants at the Longhorn Army Ammunition Plant (Talbot et al., 2002).

The *GSSHA* model fully couples atmospheric inputs, the overland flow plane, stream network and sub-surface media in physically meaningful, mass-conserving method providing utility to the USACE that no other model does, including:

- Complete linkage to the DoD WMS
- The ability to simulate infiltration with the most complete equations (Richards' equation) and a variety of proven simplifications of Richards' equations providing spatially and temporally varied groundwater recharge.
- 2-dimensional overland sediment erosion, transport and deposition modeling.
- Dynamic water and sediment routing, fully coupled to overland flow plane.
- Full documentation – User's Manual (Downer and Ogden, 2003a), Primer (Downer et al., 2003) and Tutorials.
- Full access to source code.

<u>Current Developments Nearing Completion Include:</u>

- Fully dynamic stream routing with the shock capturing scheme MESH (Meselhe et al., 1997).
- Inclusion of reservoirs, lakes, wetlands, and hydraulic structures in the stream network.
- Continuous, long-term, overland sediment erosion, transport and routing of an unlimited number of sediment sizes and densities.
- Coupled sediment and contaminant transport using common transport equations.
- Parallel version of the model for solving large problems with fine grid resolution.

<u>Planned Development Includes:</u>

- Development and inclusion of improved overland and channel sediment erosion algorithms.
- Chemical specific kinetics routines for contaminant transport.
- Sub-surface pipe flow networks for urban hydrology.
- Seasonal variability of parameter values.

The GSSHA model's ability to explicitly include spatial heterogeneity makes it ideal for design projects and for analysis of future conditions. Figure 1 shows a section of the Clinton River basin being simulated for the Detroit District. The polygons represent the original land use shape file. The grid with filled squares represents the GSSHA interpretation of that information. The different color grid cells indicate the different land uses. As can be seen in the figure, the model representation of land use clearly preserves both the total coverage and location of different land use types. If one imagines rainfall on the landscape depicted in Figure 1, it is easy imagine how the configuration of land use affects runoff and flow. It is also easy to see how changes in land use can be explicitly represented in the model.

## Summary

The utility of simple models such as HEC-1 is undeniable. Such models have been used for decades and have seen wide application. As useful as simple models have been, they are not necessarily the best class of model for all purposes and certainly improvements in hydrologic analysis can be made. Simple, lumped-parameter, empirical models are best suited for analysis of larger systems over extended periods of time. Physically-based, distributed models compliment the utility of the simple models. This class of model is thought to be superior for analysis at fine time scales (events), in certain hydrologic conditions (arid regions), and for analysis of changes in the hydrologic system, such as land use change, BMPs, or changing meteorological conditions. Employed in companion, simple models can serve to quickly identify areas requiring more rigorous study with the physically-based, distributed approach. In the future, this may prove to be the best application of both modeling approaches.

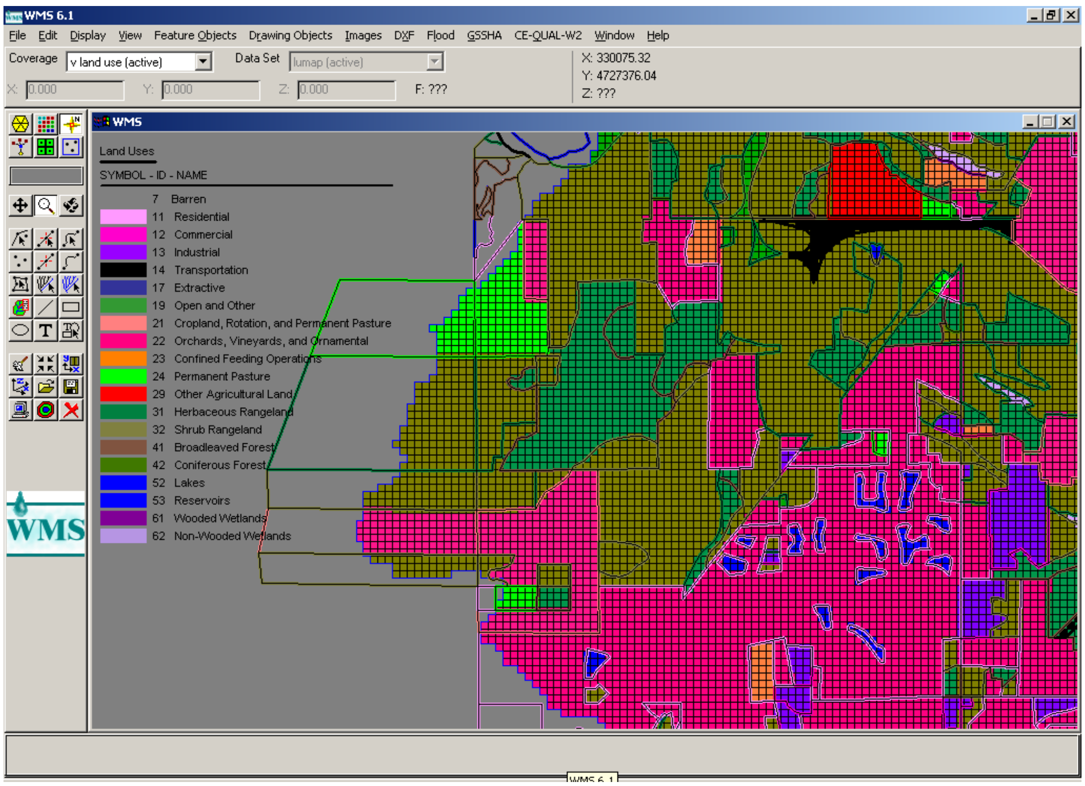


**Figure 1.** GSSHA representation of land use with 50 m grid.

## References

Abbott, M.B., J. B. Bathurst, J. A. Cunge, P. E. O'Connell, and J. Rasmussen. (1986). An introduction to the European Hydrological System-Systeme Hydrologique Europeen, 'SHE'-1: History and philosophy of a physically-based, distributed modeling system, *J. Hydrol*., **87:** 45-59.

Arnold, J. G., P. M. Allen, and G. Bernhardt. (1993). "A comprehensive surface-groundwater flow model", *J. Hydrol*., **142:** 47-69.

Beven, K. J., Distributed models In: M. G. Anderson and T. P. Burt, Eds. (1985). *Hydrologic forecasting*, Wiley, New York, N. Y., pp. 405-435.

Beven, K. J. (1989). “Changing ideas in hydrology - The case of the physically-based models”, *J. Hydrol.,* 105: 157-172, 1989.
Bergman, M.J., and Donnangelo, L.J. (2000). “Simulation of Freshwater Discharges from Ungaged Areas to the Sebastion River, Florida”, Journal of the American Water Resources Association, 36(5): 1121-1132.
Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Jr., Donigian, A.S., Jr., and Johanson, R.C., (1997). Hydrological Simulation Program--Fortran:User's manual for version 11: U.S. Environmental Protection Agency, National Exposure Research Laboratory, Athens, Ga., EPA/600/R-97/080, 755 p.
Carrubba, L. (2000). “Hydrologic Modeling at the Watershed Scale Using NPSM.” Journal of the American Water Resources Association, 36(6): 1237-1246.
Chiew, F. H. S, M. J. Stewardson, and T. A. McMahon (1993). “Comparison of six rainfall-runoff modeling approaches”, *J. Hydrol.* 147: 1-36.
Daraio, J. A. (2002) *Assessing the effects of rainfall kinetic energy on channel suspended sediment concentrations for physically-based distributed modeling of event-scale erosion*, Masters Thesis, University of Connecticut.
Doe, W. W., B. Saghafian, and P. Y. Julien (1996). “Land-use impact on watershed response: the integration of two-dimensional hydrological modeling and geographical information systems”, *Hydrol. Proc.*, 10, 1503-1511.
Downer, C. W. (2002). *Identification and Modeling of Important Stream Flow Producing Processes in Watersheds,* PhD Dissertation, Univ. of Connecticut.
Downer, C. W., and Ogden, F. L. (2003a). *GSSHA User’s Manual*, *Gridded Surface Subsurface Hydrologic Analysis Version 1.43 for WMS 6.1*, ERDC Technical Report, Engineer Research and Development Center, Vicksburg, Mississippi.
Downer, C. W. and F. L. Ogden (2003b). “Effects of model complexity and parameter assignment in the prediction of runoff and soil moistures at the watershed scale”, *Wat. Resourc. Res.,* 39(3).
Downer, C.W., F.L. Ogden, W. Martin, and R.S. Harmon (2002). “Theory, Development, and Applicability of the Surface Water Hydrologic Model CASC2D”, *Hydrological Processes*, 16(2):255-275.
Downer, C. W., J. Nelson, and A. Byrd (2003). Primer, *Using WMS for GSSHA Data Development: for use with GSSHA 1.42b and WMS 6.1*, ERDC/CHL TR-03-2.
Gan, TY and SJ Burges (1990a) “An assessment of a conceptual rainfall-runoff model’s ability to represent the dynamics of small hypothetical catchments, 1, Models, model properties, and experimental design.” *Wat. Resour. Res.* 26(7): 1595-1604.
Gan, TY and SJ Burges (1990b). “An assessment of a conceptual rainfall-runoff model’s ability to represent the dynamics of small hypothetical catchments, 2, Hydrologic responses for normal and extreme rainfall.” *Water Resources Research* 26(7): 1605-1619.
Hughes, DA and AB Beater (1989). “The applicability of two single event models to catchments with different physical characteristics.” *Hyd. Sci.* 34 (1) 2: 63-78.
Johnson, B.E., (1997). *Development of a Storm Event Based Two-Dimensional Upland Erosion Model*, Ph.D. Dissertation, Dept of Civil Engineering, Colorado State University, Fort Collins, CO 80523.

Klemeš, V. (1986). “Operational testing of hydrological simulation models”, *Hydrol. Sci. J.*, 31: 13-24.
Loague, K. M. and R. A. Freeze (1985). “A comparison of rainfall-runoff modeling techniques on small upland catchments,” *Wat. Resour. Res.,* 21(2): 229-248.
Meselhe E.A., Sotiropoulos F., and Holly F.M. Jr. (1997). “Numerical Simulation of Transcritical Flow in Open Channels” *J of Hyd Engr*, ASCE, vol. 123 (9), Sept.
Michaud, J. and S. Sorooshian (1994). “Comparison of simple verses complex distributed runoff models on a midsized semiarid watershed,” *Wat. Resour. Res.*, 30(3): 593-605.
Munson, A.D. (1998). “HSPF Modeling of the Charles River Watershed.” M.S. Thesis, Department of Civil Engineering, Massachusetts Institute of Technology.
Naef, F. (1981). “Can we model the rainfall-runoff process today?”, *Hydrol. Sci. Bull.* 26(3): 281-289.
Neidzialek, JA and FL Ogden (2003). “Physics-Based Distributed Rainfall-Runoff Modeling of Urbanizing Watersheds Revisited with GSSHA”. *ASCE J. Hydrologic Engineering*, submitted.
Nelson, E.J. (2001). *WMS v6.1 HTML Help Document*, Environmental Modeling Research Laboratory, Brigham Young University, Provo, UT.
Nikolaidis, N. P., H. Heng, R. Semagin, and J. C. Clausen (1996). Final technical report, Non-point source studies of nutrients in glaciated soils of Connecticut, Part 1/4, Exec. summary: Nonlinear response of a watershed to nitrogen loading, Department of Environmental Protection, State of CT, Office of Long Island Sound Programs, 79 Elm Street, P.O. Box 5066, Hartford, CT 06102, 170 pp.
Ogden, F.L., and A. Heilig (2001). “Two-Dimensional Watershed-Scale Erosion Modeling with CASC2D,” *in* Landscape Erosion and Evolution Modeling, (R.S. Harmon and W.W. Doe III, eds.), Kluwer Academic Publishers, New York, ISBN 0-306-4618-6, 535 pp.
Ogden, F.L. and P.Y. Julien (2002). “*CASC2D:* A Two-Dimensional, Physically-Based, Hortonian, Hydrologic Model,” *in Mathematical Models of Small Watershed Hydrology and Applications*, (V.J. Singh, and D. Frevert, eds.), Water Resources Publications, Littleton, CO, ISBN 1-887201-35-1, 972 pp..
Ogden, F.L., H.O. Sharif, S.U.S. Senarath, J. A. Smith, M.L. Baeck, and J.R. Richardson (2000). “Hydrologic Analysis of the Fort Collins, Colorado, Flash Flood of 1997,” *J. Hydrol.*, 228: 82-100.
Ponce, V. M. and R. H. Hawkins (1996). “Runoff Curve Number: Has it Reached Maturity?,” *J. Hydrol. Engr.*, 1(1): 11-19.
Refsgaard, J.C., and J. Knudsen (1996). “Operational validation and intercomparison of different types of hydrological models,” *Wat. Resour. Res.*, 32: 2189-2202.
Sanchez, R. R. (2002). *GIS-Based Upland Erosion Modeling, Geovisulization and Grid Size Effects on Erosion Simulations with CASC2D-SED.* PhD Disseration, Colorado State University.
Senarath, S.U.S., F.L. Ogden, C.W. Downer, and H.O. Sharif (2000). “On the calibration and verification of two-dimensional, distributed, Hortonian, continuous watershed models,” *Wat. Resour. Res.*, 36(6): 1495-1510.
Talbot, C.A., C.W. Downer, H.C. Lin, S.E. Howington, D.R. Richards (2002). “Computational methods for simulating interaction between surface &

subsurface hydrologic systems," in *Proceedings of the 14th International Conference on Computational Methods in Water Resources*, *23-28 June 2002*, Elsevier Science, Amsterdam, The Netherlands.

US Army Corps of Engineers (USACE) (1985). *HEC-1, flood hydrograph package: User's manual*, Hydrol. Eng. Cent., Davis, California.

Wang, M. and A. T. Hjelmfelt (1998). "DEM base overland flow routing model," *J. Hydrol. Engr.* 3(1): 1-8.

Woolhiser, D. A. (1996). "Search for physically-based runoff model - A hydrologic el dorado?," *J. Hyd. Engr.*, 122 (3): 122-129.